



Impacts of unconventional gas development on China's natural gas production and import



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ABSTRACT

China has become a net importer of natural gas as a result of rapidly increasing consumption in recent years. A production peak would exist since natural gas is an exhaustible resource. As conventional natural gas production peak approaches, the development of unconventional natural gas is attracting increasing attention. China's unconventional natural gas reserves are abundant, but exploration is still in its infancy stage. Thus, with the increasing quest for low-carbon development and China's natural gas price reform, studying the impacts of unconventional gas development on China's natural gas supply and price reform under different scenarios has practical significance. In this paper we predict China's natural gas production trends in different scenarios and forecast natural gas demand. This paper concludes that the exploitation of unconventional natural gas will greatly improve China's annual natural gas production, and delay the production peak year. This is important for China's natural gas supply security as it can decrease dependence on imported gas. Furthermore, as the cleanest fossil fuel, it will enable more time and space for renewable energy development given the many costs and controversies surrounding its development in China.

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Abbreviations: CCS, Carbon Capture and Storage; bcm, billion cubic meters; tcm, trillion cubic meters; IEA, International Energy Agency; EIA, U.S. Energy Information Administration; URR, Ultimate Recoverable Reserves; LNG, Liquid Natural Gas

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1. Introduction

With respect to low carbon development, the advantages of natural gas are obvious compared to other fossil fuels. Also, it compares fairly with many kinds of renewable energy in terms of competitiveness. It is true that the share of renewable energies such as biomass, hydroelectricity and solar, in the energy structure has been increasing. However, traditional fossil fuels are still dominating human's energy consumption and this situation is likely to continue for a long time, especially in developing countries like China. The popularity of renewable energy will take time because of cost and environment controversy issues, and other risks. As the cleanest fossil fuel, natural gas can help meet the demand for cleaner energy in many sectors, such as power generation and transportation. The use of natural gas has been proven to be reliable and cost-competitive, and the potential deployment of new technologies like the Carbon Capture and Storage (CCS) could continue to enhance the sustainable environmental advantages of natural gas.

As the world's largest emitter of greenhouse gases, and because of environment degradation, such as the increase of hazy weather, as well as the increasing dependence on imported oil and gas, China's energy consumption is currently facing greater constraints.

China's current energy consumption is still dominated by coal. Based on [1], coal accounts for 68.5% while oil, hydroelectric and natural gas share 17.7%, 7.12% 4.7% respectively of China's energy consumption. Though the proportion of gas in the energy structure is less than most developed countries, and the world average (23.9%), gas consumption growth and foreign dependence is increasing rapidly. Based on [2], between 2001 and 2010, average gas consumption growth rate was 16.07%, and China had become a net gas importer since 2007. Its foreign gas dependence was over 30% at the end of 2013. This is due to the need for low-carbon and low-cost fuel which could sustain economy growth, as large scale development of renewable or clean energies still needs time.

Natural gas demand in the European countries grows due to the fuel's convenience and environmental benefits and, consequently, there is high import dependence [3]. Based on Ref. [4] China could become the second largest gas importer after the EU-27 or even surpass it. She is expected to account for a quarter of global gas demand growth by 2035.

With the rapid growth of consumption and foreign dependence, gas supply security is getting more attention. Hubbert [5] proposes that for any non-renewable resource, its production would initially go through a stage of exponential growth, reach a peak, and decrease rapidly until depletion. During the lifecycle of the resource, the production curve is consistent with the integral calculus theory.

Since the peak theory was proposed, a number of geologists have studied global and regional reserves and productions of oil, coal and natural gas. For example, UK Energy Research Centre [6] concluded that conventional oil production peak would reach before 2030 or possibly 2020. Nashawi et al. [7] predicted that oil production would peak in 2014. Owen et al. [8] predicted that oil production will peak before 2015. IEA [9] predicted that a peak would be reached before 2020 due to severe supply growth constraints beginning in 2010.

Similarly, coal peak has also drawn many attentions. Coal production had already peaked in more than 20 countries, like Japan, the United Kingdom, and Germany. Milici and Campbell Elisabeth [10] adopted the life-cycle method and demonstrated that Virginia's coal production was in a post-peak (depletion-driven decline) stage. Mohr and Evans [11] adopted a model which took into account supply and demand fundamentals, and concluded that worldwide coal production peak would be between 2010 and 2048 or 2011 and 2047. Lin and Liu [12] used Logistic and

Gaussian curves to predict China's coal peak, and the results indicated that China's coal peak would be between late 2020s and early 2030s.

Natural gas also has peak production. Some countries have already passed their natural gas production peak. In Europe, Italy's gas consumption is third after Germany and the United Kingdom. Italy's natural gas production peaked in 1994 and declined thereafter while her consumption grow steadily, thereby substantially increasing gas imports. Romania reached its natural gas production peak in 1982, and her consumption decreased correspondingly, thereby having little impact on import. Gas production in the U.K. peaked in 2000 while her consumption declined modestly in recent years, making her a net gas importer.

For natural gas's peak production, the predictions can be different and difficult due to the existence of unconventional gas. The concept "unconventional" vary with the passage of time and technology progress. Ref. [13] defines the difference between a conventional reservoir and an unconventional reservoir, and points out that unconventional reservoirs are best described using the Resource Triangle. From the current point of view, unconventional gas includes tight gas, coalbed methane, shale gas, and possibly methane hydrate in the future ([14]).

The Dutch government claimed that its natural gas would reach peak production in 2007–2008, and the nation would be a net importer of natural gas until 2025 ([15]). From historical data, the assertion of the Dutch government is right as the country's gas production shows a declining trend after 2008. However, there are also counterexamples. Hubbert [5] predicted that the natural gas production of the U.S. would peak in 1973 with a production of about 39.64 bcm, and the production would subsequently decline. However, due to the discovery of reserves in the Gulf of Mexico and the development of unconventional natural gas, natural gas production of the U.S. began to rise again. Reynolds and Kolodziej [16] predicted that the gas peak of North America would be reached in 2013. Based on recent historical data, the upward trend seems to continue.

For the world's gas production, Bentley [17] predicted that global natural gas production would begin to decline from 2020; Edwards [18] forecasted that conventional gas production would peak at 2.89 tcm in 2040; Zhang et al. [19] forecasted that natural gas production would peak at 3.45 tcm in 2030–2035; Campbell and Heaps [20] modeled natural gas production and predicted that it would peak at 2.84 tcm in 2021; Al-Jarri and Startzman [21] forecasted that conventional gas production would peak at 2.72 tcm in 2011 with an URR of 186.08 tcm. Al-Jarri and Startzman [22] modeled conventional natural gas production by countries and predicted a peak at 2.62 tcm in 2014–2017 with URR at 265.55 tcm; [23] predicted a peak at 2.34 tcm in 2019 with URR at 243.42 tcm; [24] modeled conventional gas production by assuming URR to be 193.63 tcm, and predicted a peak at 2.64 tcm between 2008 and 2014; Laherrere [25] estimated the URR to be 264.04 tcm and predicted a peak production at 3.52 tcm in 2020. By comparing the results of these researches, it can be seen that the difference among the predictions of peak year of global natural gas production is mainly due to the different URR adopted, and most of these predictions only focus on conventional gas. Lin and Wang [26] also used Logistic and Gaussian curves to predict China's gas peak, and the result indicated that China's gas would peak in early 2020s, but the prediction is only on conventional gas.

As more countries are close to their conventional gas production peak, the quest for low-carbon path and the success of the U.S. shale gas revolution has increased attention on the development of unconventional natural gas.

Global natural gas recoverable reserves are estimated at 850 tcm under existing technology level, of which unconventional natural gas (including coalbed methane, tight gas, and shale gas)

account for 45% ([9]). As the technology evolves, key technical bottlenecks will be removed. Due to the increasing instability in oil prices coupled with regional instability, unconventional resources should be considered as a bridging option between rapidly depleting conventional resources and the nascent evolving renewable and thorium (nuclear) based energy sources ([27]).

Though the potential of unconventional gas has been known for centuries, with the first shale gas wells drilled in the 1820s. However, it is only with recent technological improvements that extracting the resources has become economically viable. Among countries that have developed unconventional natural gas earlier, the U.S. is particularly prominent. The low exploitation cost of unconventional gas is mainly ascribed to the development and application of horizontal drilling and hydraulic fracturing technology, and more importantly, government's preferential policies.

In the case of China, there are suggestions that as an exhaustible resource and due to environmental issues, unconventional natural gas should not be exploited in large scale. However, the present reality in China may not agree with these suggestions. Firstly, China is currently experiencing rapid urbanization and industrialization, which is characterized by rigid energy demand, and as a result, the dependence on foreign fossil fuel including natural gas will rise. Secondly, China's natural gas prices are still government-guided, and domestic gas prices are substantially lower than international natural gas prices. Thus, rising dependence on foreign gas will put increasing pressure on price. Therefore, the debate on developing unconventional natural gas in China is worth exploring.

This paper attempts to forecast China's natural gas supply, including conventional and unconventional natural gas in different scenarios in order to study the practical significance of unconventional gas exploitation and provide relevant policies for developing unconventional natural gas.

The rest of this paper is organized as follows. The second section describes the amount of natural gas resources in China. The third section predicts China's gas supply in different scenarios. The fourth section predicts China's gas demand and foreign dependence using Grey method. The last section provides the conclusions and suggestions.

2. China's natural gas resources

2.1. Conventional natural gas

As mentioned above, the difference in estimations on peak year and production is mainly due to the different URR used. The estimations of global natural gas URR used by researchers are quite different, and the comparison is shown in Table 1. It can be seen that the estimations vary greatly and the largest URR is about twice the smallest. Therefore, in forecasting natural gas production, it is important to set appropriate URR scenarios.

In order to maintain the consistency of conventional and unconventional gas URR, this paper adopts the natural gas URR from Ref. [28], which was given in L, BG and H scenarios. Table 2 shows the conventional gas URR of China in these three different

Table 1
World's conventional natural gas URR estimations of different studies (tcm).
Source: [28].

Al-Fattah and Startzman [22]	Campbell and Heaps [20]	IEA [9]	Imam et al. [24]	Laherrere [25]
265.55	254.73	435.29	243.42	265.30

Table 2
Conventional gas URR in different scenarios (tcm)
Source: [28].

Region	L	BG	H
World	269.32	324.89	460.68
China	5.28	5.28	12.82

scenarios, and it can be seen that China's conventional gas accounts for about 2–3% in the conventional gas URR of the world.

2.2. Unconventional natural gas

China's Ministry of Land and Resources made a conservative estimate of its total recoverable unconventional gas reserves at 15–30 tcm, while the estimations of EIA and IEA are more optimistic at 36 tcm and 50 tcm respectively ([3]).

Unconventional natural gas consists mainly of shale gas, coalbed methane, and tight gas. So we start the study by analyzing the three gases separately.

2.2.1. Shale gas

China's technically recoverable shale gas resource is 36.1 tcm. Natural gas resource of the U.S. amounts to 72.01 tcm, with technically recoverable shale gas resource at 24.41 tcm, accounting for 34% of the total. Shale gas will make the largest contribution to total natural gas output. It will account for 46% of total natural gas production in the U.S. by 2035 ([29]).

China's shale gas resource is richer than that of the U.S. But unlike the U.S., the prospects of China's shale gas may not be so optimistic. There are many impediments: poorer geological conditions, mining right, shortage of water, higher degree of government regulation, immature natural gas industry development pattern, as well as higher degree of monopoly in the oil and gas industry. Till now, there is little shale gas production in China.

Shale gas in China is still at the initial stage as resource exploration and exploitation has not been adequately carried out. Estimations of China's shale gas resources vary greatly, as shown in Table 3.

The prediction of China's natural gas production also requires unconventional natural gas URR. For consistency, shale gas URR is adopted from Ref. [28], which is 14.33 tcm (in all three scenarios), and accounts for about 15–24% of world shale gas URR.

2.2.2. Coalbed methane

Coalbed methane has proven to be a major unconventional resource over the past few decades. Coalbed methane accounts for approximately 9.5% of the total gas production and reserves in the USA ([31]).

China has rich coalbed methane resource. The estimation of coalbed gas resource for a particular region tends to vary in different studies, and this can be shown in Table 4. According to [32], coalbed methane resources in China ranked third in the world, following Russia and Canada. China's coalbed methane area amounted to 4.15 million square meters. The coalbed methane reserves within 2000 m amounted to about 36.8 tcm, within 1000 m amounted to 14.3 tcm (recoverable reserves about 6.3 tcm), within 1000–1500 m amounted to 10.6 tcm, and within 1500–2000 m amounted to 11.9 tcm.

Coalbed methane development in China started early, beginning in the early 1980s. However, due to funding, technology, policy and market constraints coupled with other factors, its development has been slow. In recent years, there have been series of development policies. According to [33], in 2009 coalbed

Table 3

Shale gas resource estimation in different studies.

Source: [30].

Region	Resource (tcm)	Reference	Year
China	100	Rogner	1997
Center Asia and China	99.9	Kawata and Fujita	2001
Chian (Main Region)	15–30	Colorado School of Mines;John B. Curtis	2002
China	35	Reserch Institute of Petroleum Exploration and Development	2008

Table 4

Coalbed methane resource estimation in different studies (tcm).

Source: [28].

Region	Resource(tcm)	Reference	Year
world	237.63	Campbelland Heaps	2009
China	26.4		
world	79.69–264.24	Aluko	2001
China	27.96–51.27		
world	77.98–245.66	Boyer and Qinghao	1998
China	27.99–32.74		
world	127.49–349.26	Cramer et al.	2009
China	31.68–34.3		
world	93.47–201.47	Kuuskra and Stevens	2009
China	18.48–33.55		

Table 5

China's coalbed methane URR of different scenarios (tcm).

Source: [28].

L	BG	H
2.77	8.05	31.68

Table 6

China's tight gas URR of different scenarios (tcm).

Source: [28].

L	BG	H
1.51	4.02	10.31

methane production amounted to 1.33 bcm; and China's ground coalbed methane production capacity reached 3.5 bcm in 2010, but yield was only 1.5 bcm. Coal mine gas drainage reached 6.17 bcm in 2009, with an average annual growth rate of 28%. China's coalbed methane pipeline construction also started, and 4 long-distance pipeline have already been built or under construction with a total length of 280 km and annual gas transmission capacity of 5.5 bcm. However, compared to conventional gas production, China's coalbed methane production is still small.

For consistency, the estimations of coalbed methane URR in China in L, BG, H scenarios are also from Ref. [28] and shown in Table 5. It can be seen that the URR differs significantly in different scenarios, and China's coalbed methane URR accounts for about 13–24% of world total coalbed methane URR.

2.2.3. Tight gas

Tight gas is also called tight sandstone gas, and it exists in almost all oil gas area. It was first found in the San Juan basin in the U.S. in 1927, and the large Elm Voss compact sandstone gas field was discovered in Canada Alberta basin western deep depressions in the North in 1976. Since 1971 when Zhongba Gas

Field was discovered, China had begun to gradually and systematically study the tight sandstone gas field.

China's tight gas resource is more than 120 tcm, and the reservoirs are mainly distributed in the Sichuan Basin, Erdos Basin, Songliao Basin, Bohai Bay Basin, Qaidam Basin, Tarim Basin, and Junggar Basin ([34]).

We estimate the natural gas output in L, BG, and H scenarios, and the tight gas URR estimations in these scenarios are also from [28] and shown in Table 6 It accounts for about 6–8% of the world's tight gas URR.

3. Predictions of China's natural gas production in different scenarios

Logistic curve has been widely used to model population growth, and [35] used it to model oil production. Gaussian curve shares a similar theoretical basis as the Logistic curve. That is the Central Limit Theorem, which states that a sufficiently large number of independent random variables, each with finite mean value and variance, will follow the approximately normal distribution ([36]). Bartlett [37] used both Gaussian and Logistic curve to fit historical data of the oil production of the U.S. and the world. Brandt [38] used six models (Hubbert, Linear, Exponential, Asymmetrical Hubbert, Asymmetrical Linear, Asymmetrical Exponential) to test Hubbert's peak theory; and by comparing the results of the three symmetric models, Brandt [38] pointed out that Hubbert model is the most widely applicable model, as no more than half of the regions can be well described by the linear or exponential models. However, when attempting to understand previous production, symmetric models are not satisfying, but they can be relatively more useful in prediction. Lin and Liu [12] predicted coal peak in China by using the Logistic and Gaussian curves. Lin and Wang [26] also predicted gas (mainly conventional gas) peak by using the Logistic and Gaussian curves, and the results of the two methods differ modestly.

Logistic curve model fits historical data to standard Logistic functions, and URR is adopted as the up limit of total yields.

$$Q = \frac{URR}{1 + e^{-(t - t_{max})/w}} \quad (1)$$

In Eq. (1), Q is cumulative gas production, URR equals cumulative of historical production plus remaining recoverable reserves; t is year, t_{max} is the year of peak; w is a parameter. We adjust t_{max} and w so as to minimize the residual sum of squares between the fitting and observed values. Then the t_{max} is peak time, and the production of that year is peak production.

In this part, the URR of China's conventional and unconventional natural gas and Logistic curve model will be used to study China's natural gas supply trend. The historical consumption data comes from China Economic Information Network.

As the exploitation technology of the different types of natural gas is different, it is reasonable to predict the production of the different types of natural gas separately. As the development of China's unconventional natural gas is in the initial stage, the exploration results of the resources are largely inaccurate while the annual output data is scarce. Thus, we make some assumptions.

In 1990, China's conventional natural gas production accounted for 95.1% of total output and tight gas production accounted for only 4.9%. Conventional natural gas accounted for 84.7% in 2000 while the contribution of tight gas rose to 15.3% in the same period. In 2010, tight gas accounted for 24.6% of total gas output, and it has been the main support for the rapid increase in natural gas production in recent years. From the view of technology and the mining conditions, the development of tight gas is the most realistic, as it is of great certainty.

The development of China's shale-gas industry has progressed over the past few years, "but far more remains to be done than has been accomplished if the nation's ambitious production targets are to be met. Here is a quick rundown on the status of the industry and the daunting challenges ahead" ([39]). Because of the uncertainty in shale gas development, and the characteristics of China's coalbed methane resource endowments, priority is given to coalbed methane development than shale gas. According to the

"12th Five-Year Plan" of coalbed methane and shale gas, the annual production of shale gas in China will reach 6.5 bcm, while that of coal bed methane will be 30 bcm, about five times that of shale gas, in 2015. According to the plan, it is also said that China will make effort to produce 60–100 bcm shale gas in 2020. For such plan, it is generally believed that 6.5 bcm shale gas production in 2015 can be basically achieved, but the 2020 target faces a lot of difficulty. In April 2011, the first domestic shale gas horizontal well was completed in Weiyuan County, Sichuan.

As the historical production data of natural gas in China include conventional and tight gas, we split the data into two parts and predict the production of conventional gas and tight gas separately. The results are shown in Figs. 1 and 2.

For coalbed methane production to reach 30 bcm in 2015, it needs to maintain an average annual growth of 33%. With the strong planning support, we assume that the increase can be sustained till 2020. Given that it is feasible to reach the goal of 6.5 bcm shale gas production in 2015 while the 2020 goal is uncertain, we set 3 scenarios: 10%, 30% and 50% average growth rate between 2015 and 2020. We predict coal bed methane and shale gas production with these assumptions and using the Logistic curve. The results are shown in Fig. 3 and 4. Peak year and production of the different gases are shown in Table 7.

The total production of the different kinds of natural gas is shown in Fig. 5. For comparison purpose, the production of conventional natural gas in L/BG scenario is also shown in Fig. 5. It can be seen that the exploitation of unconventional gas will significantly increase the annual natural gas production, and delay the arrival of the peak year.

If the production of each gas can be reached in L scenario, there may be two peaks. Conventional gas, tight gas, coalbed methane and shale gas production would increase until about 2025. After the peak of the other kinds of gas, shale gas production still

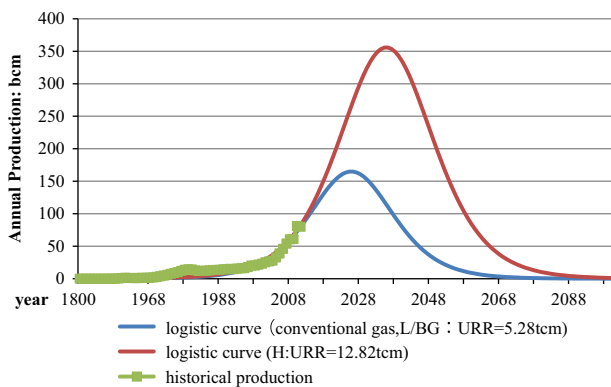


Fig. 1. Logistic predictions of China's conventional natural gas production.

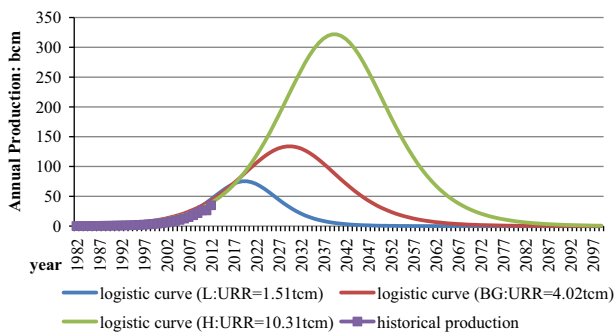


Fig. 2. Logistic predictions of China's tight gas production.

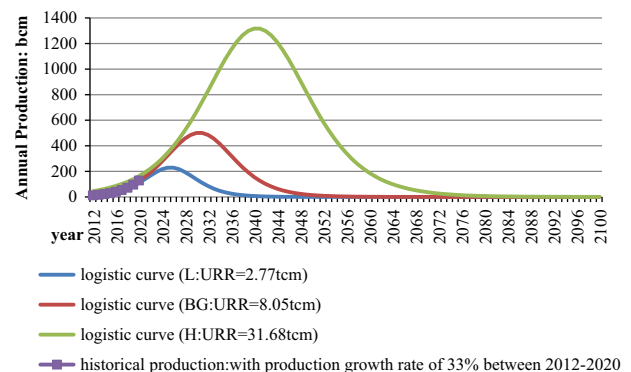


Fig. 3. Logistic predictions of China's coalbed methane production.

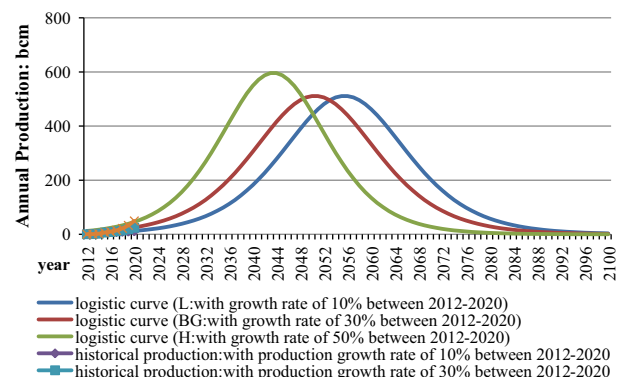
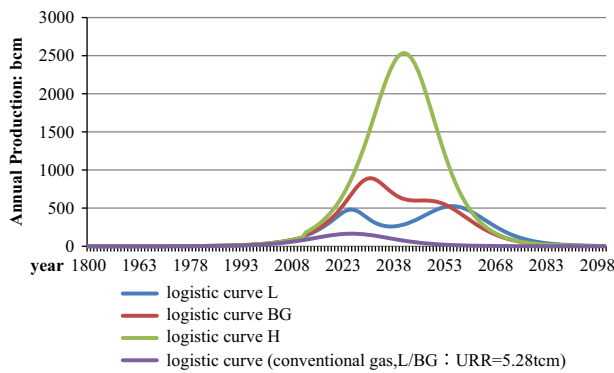
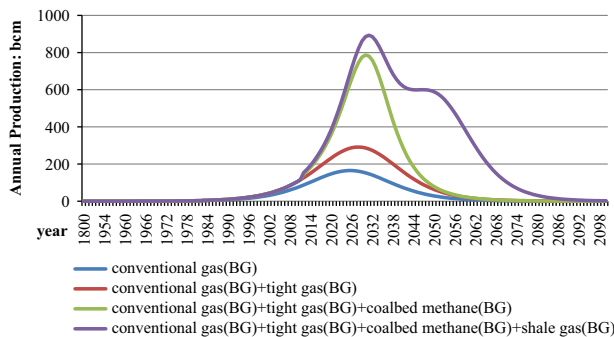


Fig. 4. Logistic predictions of China's shale gas production.

Table 7

Peak year and peak production predictions of different gases.

Gas item	Conventional gas			Tight gas		
Scenario	L	BG	H	L	BG	H
Peak year	2025	2025	2035	2020	2030	2040
Peak production(bcm)	164.79	164.79	355.75	75.25	133.80	321.77
Gas item	Coal bed methane			shale gas		
Scenario	L	BG	H	L	BG	H
Peak year	2025	2030	2040	2055	2050	2043
Peak production(bcm)	228.72	500.52	1316.95	510.92	510.92	595.71
Gas item	Total					
Scenario	L		BG		H	
Peak year	2025	2055	2031		2041	
Peak production(bcm)	481.14	527.01	893.33		2535.10	

**Fig. 5.** Logistic predictions of China's total gas production.**Fig. 6.** Logistic predictions of China's total gas production in different develop scenarios.

increase, though the increase could not offset the decrease in the other kinds of gas. After about 2035 though conventional gas, tight gas and coalbed methane production are falling, the increase in shale gas production would be significant enough to keep the trend up until about 2055. While in the BG scenario, conventional gas would first reach its production peak in about 2025 while unconventional gas production would still increase. The increase in the latter can offset the decrease in conventional gas, and the total gas production would peak at 893.33 bcm in early 2030s. In the H scenario, the URR of total gas is about 69.14 tcm, more than twice the BG URR (31.68 tcm). The total production in the H scenario would peak with about 2535.1 bcm in early 2040s, and the peak production would be about three times the peak production in the scenario BG.

For better comparison, we also present the predictions of different development scenarios, as shown in Fig. 6 (the URR and shale gas development are both in BG scenarios). If only conventional gas is developed, China's gas production would peak at 164.79 bcm in 2025. If conventional and tight gases are jointly

developed, the peak at 291.28 bcm can be delayed to 2028. If adequate support is provided towards the development of coalbed methane, the peak at 786.89 bcm can be delayed to 2030. If the production of shale gas can be added, the peak at 893.33 bcm can be delayed to 2031. After the peak, gas production would decline gradually and the share of shale gas in total gas production would be increase. From a practical point of view, the development of tight gas is of more certainty. If coalbed methane and shale gas could be developed smoothly and simultaneously according to plan, production peak year would delay, and there will be substantial increase in production. This will have major implications for natural gas consumption and energy security in China.

4. Prediction of China's natural gas demand and import trend

4.1. Grey model

Grey theory is used for dealing with the problem of data scarcity with many influencing factors. By using GM(1,1) calculation, Grey model predicts by extending the existing trend to the future. In order to get reliable results, modeling requires complete information. However, in a grey system we do not have complete information. In order to solve this contradiction, grey modeling data are required to follow the law of grey information and clear result. Taking natural gas demand forecasts as an example, natural gas consumption is the basic data required. Natural gas terminal consumption includes residential, commercial, chemical, and power generation uses, and is therefore influenced by many factors, while annual natural gas consumption is specific, so the demand prediction of natural gas follows the law of grey theory.

Zhou et al. [40] have also forecasted natural gas demand using the grey model and historical data between 1990 and 2004. Ma and Wu [41] used dynamic GM(1,1) model of the grey theory to forecast natural gas consumption and production in China. Introducing two kinds of basic forecasting methods – grey forecast and one-element linear regression, and in combination with the actual situation of coal mines, Jing et al. [42] predicted the amount of gas emission and compared the accuracy of the forecast value of the two methods. The results showed that the model GM(1,1) of the grey forecast is better than the one-element linear regression in accuracy of forecast value.

In grey model, time series $X^{(0)}$ has n observations, $X^{(0)} = \{X^{(0)}(1), X^{(0)}(2), \dots, X^{(0)}(n)\}$, generating new sequence by accumulation: $X^{(1)} = \{X^{(1)}(1), X^{(1)}(2), \dots, X^{(1)}(n)\}$,

$$X^{(1)}_{(k+1)} = X^{(1)}_{(k)} + X^{(0)}_{(k+1)} \quad k = 0, 1, 2, \dots, n. \quad (2)$$

Table 8
Relative error of different GM (1, 1) model prediction.

Data series		1980–2010	1991–2010	1993–2010	1994–2010	1996–2010	2001–2010
Parameter estimation	α	−0.11	−0.14	−0.14	−0.14	−0.15	−0.16
	μ	−9.20	45.90	65.02	76.49	105.38	229.70
Max relative error (%)		94.19	50.69	45.05	59.32	68.10	95.70
Min relative error (%)		17.92	4.24	0.30	1.03	0.32	0.23
Average relative error (%)		83.97	22.42	14.81	13.12	10.16	12.83

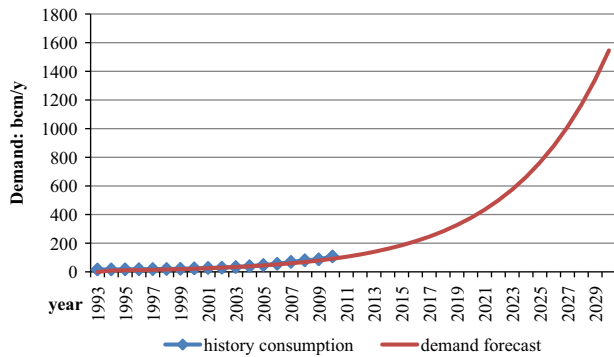


Fig. 7. Prediction of China's natural gas demand based on Grey model.

the corresponding differential equation GM(1,1) model is:

$$\frac{dX^{(1)}}{dt} + \alpha X^{(1)} = \mu \quad (3)$$

where α is called the development grey number; μ is known as endogenous control grey number. $\hat{\alpha}$ is set as an unknown parameter vector to be estimated, and $\hat{\alpha} = (\alpha, \mu)^T$, and can be obtained by using the least square method. The solution is as follows:

$$\hat{\alpha} = (B^T B)^{-1} B^T Y_n \quad (4)$$

$$B = \begin{pmatrix} -\frac{1}{2}(X_{(2)}^{(1)} + X_{(1)}^{(1)}), & 1 \\ -\frac{1}{2}(X_{(3)}^{(1)} + X_{(2)}^{(1)}), & 1 \\ \dots & \dots \\ -\frac{1}{2}(X_{(n)}^{(1)} + X_{(n-1)}^{(1)}), & 1 \end{pmatrix} \quad (5)$$

$$Y = (X_{(2)}^{(0)}, X_{(3)}^{(0)}, \dots, X_{(n)}^{(0)})^T \quad (6)$$

Based on eqs. (5) and (6), $\hat{\alpha}$ can be obtained and we can get the prediction model:

$$\hat{X}^{(1)}(k+1) = \left[X_{(1)}^{(0)} - \frac{\mu}{\alpha} \right] e^{-\alpha k} + \frac{\mu}{\alpha}, k = 0, 1, 2, \dots, n. \quad (7)$$

The forecast of $\hat{X}^{(0)}(k+1)$ can be obtained from Eq. (7)

$$\hat{X}^{(0)}(k+1) = \hat{X}^{(1)}(k+1) - \hat{X}^{(1)}(k) \quad (8)$$

4.2. China's natural gas demand prediction

In our model, $X^{(0)}$ represents historical data of natural gas consumption, and $X^{(1)}$ represents new sequence by accumulation. Based on the estimation of $\hat{\alpha}$ from Eqs. (4), (5) and (6), we get the prediction Eq. (7), and by extending n , we get the prediction of future gas demand from Eqs. (7) and (8).

Grey prediction model is more sensitive to the length of the data. If the series are short, certain information may be missed but the predicted results will fit the original data better. If the series are long, the original data contains more information but the predicted results may poorly fit the original data. Thus using

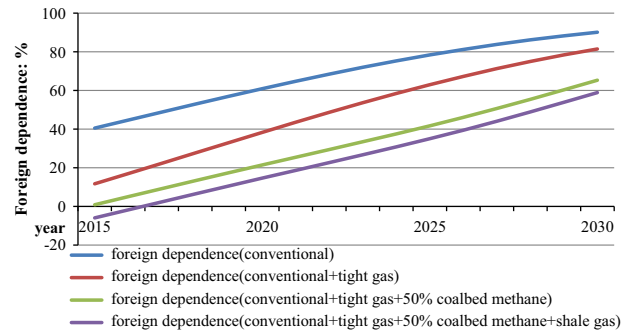


Fig. 8. Trend predictions of China's natural gas foreign dependence.

China's natural gas consumption data, we evaluate GM(1,1) model with 31, 20, 18, 17, 15 and 10 observations over 1980–2010, 1991–2010, 1993–2010, 1994–2010, 1996–2010 and 2001–2010 respectively. The estimations of $\hat{\alpha}$ for each set of observations are shown in Table 8. Considering relative error (shown in Table 8), we select GM(1,1) model with 18 observations over 1993–2010 to predict China's future demand for natural gas, and the result is shown in Fig. 7.

According to the prediction of this paper, China's natural gas demand would be 185.5 bcm in 2015, and 376.12 bcm in 2020, and the average growth rate between 2012 and 2030 will be about 15.18%. IEA [43] predicted that China's natural gas demand would be twice that of 2007 (69.52 bcm), making the IEA's prediction of China's natural gas demand in 2015 to be about 140 bcm. According to the forecast of China's National Energy Board, China's gas demand in 2020 would be 153.4 bcm. In the “12th Five-Year Plan” for natural gas, it is predicted that China's gas consumption would be 230 bcm in 2015 and 300–450 bcm in 2020. Considering the historical growth rate of China's gas consumption (11.77% on average between 1993 and 2010, 16.07% on average between 2001–2010) and the quest for low-carbon development, the prediction of this paper is reasonable.

4.3. Prediction of China's natural gas import trends

Based on the predictions of China's gas production in different scenarios and the forecast of gas demand, we obtain net gas import trends of China. The predictions of China's foreign gas dependence is calculated by Eq. (9) and shown in Fig. 8.

$$\text{foreign dependence} = (\text{consumption} - \text{production}) / \text{consumption} \quad (9)$$

As China's gas consumption is expected to rapidly increase for many years, foreign dependence will increase in the next two decades as Fig. 8 shows. According to Fig. 8, if only conventional gas is developed, China's foreign gas dependence would be 41% in 2015 (about twice the level in 2012), 61% in 2020 and 78% in 2025. If conventional gas and tight gas are developed together, which is a possibility, foreign dependence would be about 38% in 2020 and

63% in 2025. If coalbed methane (it should be noticed that because of low concentration, dispersed extraction etc., the consumption of coal bed methane cannot be 100%, and the current utilization is less than 50% in China. Here we assume that the utilization is 50%) and shale gas can be developed as expected, foreign dependence can be reduced to 14% in 2020 and 35% in 2025.

Due to the large size and the continuing process of urbanization and industrialization, China's gas consumption is expected to increase substantially. At the same time, with the promotion of low carbon development, rapid growth of China's natural gas consumption and foreign dependence is certain.

China's imported gas mainly includes pipeline gas and LNG (Liquid Natural Gas). Pipeline gas mainly comes from Central Asia and the Far East, while LNG mainly comes from Asia-Pacific and the Middle East. Currently global pipeline gas trading is mainly concentrated in Western Europe, while LNG trading is concentrated in the Atlantic region. Substantial increase in China's demand for natural gas will not only have impact on the international natural gas market, but will also threaten her gas supply security due to geopolitical risks.

The most urgent issue in rising foreign gas dependence for China is gas price. In recent years, there have been some fluctuations in the international market price of natural gas, but the overall trend of international prices of natural gas is rising, especially in the long run. Compared to oil, natural gas is difficult to store and replace in the short-term. With the continuous increase in China's foreign gas dependence, price control of exporting countries will increase. For example, as a result of the gas shortage in the end of 2009, China's major oil companies had to buy LNG from the international market at high prices.

On the other hand, the domestic natural gas pricing mechanism is not perfect. China's current gas prices are government-guided, and domestic natural gas prices are relatively fixed and generally lower than international prices. The price mechanism results in China's natural gas import prices higher than domestic natural gas prices. Without reform, a long-term price distortion will create serious problems for the operation and sales of natural gas in China.

Because of the development of unconventional gas, natural gas production of the U.S. will grow steadily at 56% and U.S. pipeline imports from Canada will fall by 30% between 2012 and 2040 ([44]). For China, based on the comparisons of the estimations of different scenarios, it is clear that under any scenario the best option is to accelerate the development of unconventional natural gas before completion of gas price reform, and 2030 when energy demand will significantly increase because of urbanization and industrialization.

5. Conclusions and suggestions

The estimations of natural gas reserves are quite different in many studies. As the current study shows, peak production in high URR scenario can be many times higher than that of peak production of low URR scenario. However, under any scenario, unconventional gas URR is about three to four times of conventional natural gas URR in China. The study results suggest that the exploitation of unconventional natural gas will significantly increase the annual output of China's gas, delay the peak year, secure China's natural gas supply, and reduce the country's dependence on foreign natural gas.

At the same time, in the face of concern over greenhouse gas emission reduction, and to achieve low-carbon transformation and ensure energy security, developing unconventional natural gas is an inevitable choice.

China's natural gas prices are lower than import gas price. Higher cost of imported gas and lower terminal price, rapid

growth of gas consumption, and increasing dependence on foreign gas will increase pressure on the need for natural gas price reform. The National Development and Reform Commission issued a notice in December 2011, and decided to carry out the pilot reform of natural gas price mechanism in Guangdong Province and Guangxi Autonomous Region. However, natural gas price reform will predictably face a lot of challenges, with the main one being how to cope with the situations that will be experienced during the market-oriented process. The price of natural gas will increase substantially. Therefore, unconventional natural gas development is necessary as it can partially limit the price rise associated with natural gas pricing reform.

Compared with other countries, China's unconventional natural gas exploration and exploitation technology is relatively backward and incur higher costs. One key reason is the lack of continuous government policy support, resulting in enterprises not having enough financial support and thus having no enthusiasm to implement the development and utilization of unconventional natural gas. With continuous increase in imported oil dependence and increasing competition in the exploitation and utilization of unconventional natural gas, the bottlenecks in geology, technology and infrastructure development will be eliminated, and the government will introduce specific policies to encourage unconventional natural gas development.

When it comes to the order of development, based on the historical data and our study, tight gas should be first. Dai et al. [45] has also pointed that tight gas should be given priority in unconventional gas exploration and exploitation in China. Considering cost and technology issues, the development of coalbed methane should also be given priority ahead of shale gas. IEA [46] also pointed that the production of unconventional gas, primarily shale gas, will more than triple to 1.6 trillion cubic meters in 2035, which will account for nearly two-thirds of incremental gas supply over the period while the share of unconventional gas in total gas output will rise from 14% to 32% in 2035. Most of the increase will come after 2020, as time is needed to establish a commercially viable industry. Zhao et al. [47] also proposed the specific strategies for the development of shale gas in China.

There are some concerns in the production process as unconventional gas is an intensive industrial process, and generally imposes a larger environmental footprint than conventional gas development. Verrastro [48] pointed that failure to manage some of the impacts surrounding the development of this resource at scale could seriously hamper efforts to fully realize the benefits. The impacts include water concerns, issues surrounding the public disclosure of the composition of fracking fluids, the "industrialization" of rural areas during development process, local issues related to widely differing lease arrangements, and population density. According to [13,49], there is need to pay special attention to the environmental risk and properly ensure environmental protection. IEA [46] treats these aspirations and anxieties with equal seriousness, and pointed out that although a bright future for unconventional gas is far from assured, numerous hurdles need to be overcome, especially the social and environmental concerns. The industry needs to commit to apply the highest practicable environmental and social standards at all stages of the development process. This cannot rely on the enterprises' consciousness, and three measures (laws and regulations, government regulation, and fines) need to be implemented at the same time.

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References

- [1] BP. Statistical review of world energy; 2013.
- [2] China statistical yearbook; 2011.
- [3] Ozturk M, Yuksel YE, Ozek N. A bridge between east and west: Turkey's natural gas policy. *Renew Sustain Energy Rev* 2011;15:4286–94.
- [4] Umbach F. Unconventional gas: the big demand in China. *World Rev* 2012 <http://www.worldreview.info/content/unconventional-gas-big-demand-china>.
- [5] Hubbert MK. Nuclear energy and the fossil fuels, drilling and production practice. 1st ed.. New York: The American Petroleum Institute; 7–25.
- [6] UK Energy Research Centre. Global oil depletion: an assessment of the evidence for a near-term peak in global oil production; 2009. 1-903144-0-35.
- [7] Nashawi IS, Malallah A, Al-Bisharah M. Forecasting world crude oil production using multicyclic Hubbert model. *Energy Fuels* 2010;24:1788–800.
- [8] Owen NA, Inderwildi OR, King DA. The status of conventional world oil reserves—Hype or cause for concern? *Energy Policy* 2010;38(8):4743–9.
- [9] IEA. World Energy Outlook; 2009.
- [10] Milici RC, Campbell Elisabeth VM. A predictive production rate life-cycle model for southwestern Virginia coalfields. *Geol Sur Circ* 1997;1147.
- [11] Mohr SH, Evans GM. Forecasting Coal Production until 2100. *Fuel* 2009;88:2059–67.
- [12] Lin BQ, Liu JH. Estimating coal production peak and trends of coal imports in China. *Energy Policy* 2010;38(1):512–9.
- [13] Holditch SA. Unconventional oil and gas resource development – Let's do it right. *J Unconv Oil and Gas Resour* 2013;1–2:2–8.
- [14] Song YC, Yang L, Zhao JF, Liu WG, Yang MJ, Li YH. The status of natural gas hydrate research in China: a review. *Renew Sustain Energy Rev* 2014;31:778–791.
- [15] Ministrie van Economische Zaken, Energie Rapport 2008 [in Dutch]; 2008. p. 41. (<http://www.ez.nl/dsresource?objectid=158410&type=PDF>).
- [16] Reynolds DB, Kolodziej M. North American natural gas supply forecast: the Hubbert method including the effects of institutions. *Energies* 2009;2:269–306.
- [17] Bentley RW. Global oil & gas depletion: an overview. *Energy Policy* 2002;30:189–205.
- [18] Edwards JD. Crude oil and alternative energy production forecasts for the twenty-first century: the end of the hydrocarbon era. *AAPG Bull* 1997;81(8):1292–305.
- [19] Zhang J, Sun ZD, Zhang YW, Sun YS, Nafi T. Risk-opportunity analysis and production peak forecasting on world conventional oil and gas perspectives. *Pet Sci* 2010;7(1):136–46.
- [20] Campbell CJ, Heaps S. An Atlas of oil and gas depletion. 2nd ed.. Springer-Verlag New York Inc: Jeremy Mills Publishing Limited; 2009.
- [21] Al-Jarri AS, Startzman RA. Worldwide petroleum–liquid supply and demand. *J Pet Technol* 1997;49(12):1329–38.
- [22] Al-Fattah SM, Startzman RA. Forecasting world natural gas supply. *J Pet Technol* 2000;52(5):62–72.
- [23] Imam A, Startzman RA, Barrufet MA. Multicyclic Hubbert model shows global conventional gas output peaking in 2019. *Oil Gas J* 2004;102(31):20–8.
- [24] Guseo R. How much natural gas is there? Depletion risk and supply security modeling. (www.homes.stat.unipd.it/guseo/ngastfschr1.pdf) [18.08.09].
- [25] Laherrere, JH. Etat des reserves de gaz des pays exportateurs vers l'Europe, Club of Nice; 2007 (http://www.ieh.org/Club_de_Nice/2007/) [14.01.10].
- [26] Lin BQ, Wang T. Forecasting natural gas supply in china: production peak and import trends. *Energy Policy* 2012;49:225–33.
- [27] Menon RR. Exploration and production issues in South Asia. *J Unconv Oil Gas Resour* 2014;6:39–47.
- [28] Mohr SH, Evans GM. Long term forecasting of natural gas production. *Energy Policy* 2011;39:5550–60.
- [29] EIA. Annual Energy Outlook; 2011.
- [30] Liu DX, Wang HY, Zhao Q, Liu HL. Development trend of unconventional gas resources in China. *Research Institute of Petroleum Exploration and Development Published; Advanced Materials Research*, Vols. 616–618 (2013) pp250–256.
- [31] Shah S, Totlani K. Difficulties and prospects of Coalbed methane in India as compared to North America, Difficulties and prospects of Coalbed methane in India as compared to North America. *J Unconv Oil Gas Resour* 2014;6:48–53.
- [32] Luo DK, Dai YJ, Xia LY. Economic evaluation based policy analysis for coalbed methane industry in China. *Energy* 2011;36:360–8.
- [33] Pan JP, Wang N, Han ZQ, Li SZ. Exploration and development of unconventional gas resources in China and analysis of policy recommendations, Strategic research center for oil and gas resources, ministry of land & resources. *Phys Rev C* 2011;6:19–24.
- [34] Kang YL, Luo PY. Current status and prospect of key techniques for exploration and production of tight sandstone gas reservoirs in China. *Pet Explor Dev* 2007;34(2):239–44.
- [35] Hubbert, MK. Techniques of prediction with application to the petroleum industry. In: Published in 44th Annual Meeting of the American Association of Petroleum Geologists. Shell Development Company, Dallas, TX; 1959. 43 p.
- [36] Rice J. Mathematical statistics and data analysis. 2nd ed.. New York: Duxbury Press; 0-534-20934-3.
- [37] Bartlett AA. An analysis of U.S. and World oil production patterns using Hubbert-Style curves. *Mathematical Geology*, 2000;32:1–17.
- [38] Brandt AR. Testing Hubbert. *Energy Policy* 2007;35:3074–88.
- [39] Yep E. China's Long Road to Shale-Gas Boom. *Wall Street J* 2014;26. (<http://blogs.wsj.com/moneybeat/2014/03/26/chinas-long-road-to-shale-gas-boom/>).
- [40] Zhou ZP, Li L, Zhang SY. Natural GAS demand forecast based on grey theory. *Nat Gas Explor Dev* 2006:74–6.
- [41] Ma, HW Wu Grey, YH. Predictive on Natural Gas Consumption and Production in China. In: WMWA'09 Proceedings of the 2009 Pacific-Asia conference on web mining and web-based application. Washington, DC, USA; 2009. p. 91–4.
- [42] Jing GX, Xu SM, Heng XW, Li CQ. Research on the prediction of gas emission quantity in coal mine based on grey system and linear regression for one element. *Procedia Eng* 2011;26:1585–90 (ISMSE2011).
- [43] IEA. World energy outlook; 2010.
- [44] EIA. Annual energy outlook. Early release overview; 2014.
- [45] Dai JX, NI YY, WU XQ. Tight gas in China and its significance in exploration and exploitation. *Pet ExplorDev* 2012;39(3):277–84.
- [46] IEA. Golden rules for a golden age of gas-world energy outlook special report on unconventional gas; 2012.
- [47] Zhao XG, Kang JL, Lan B. Focus on the development of shale gas in China—Based on SWOT analysis. *Renew Sustain Energy Rev* 2013;21:603–13.
- [48] Verrastro, F., Conor Branch, Developing America's unconventional gas resources benefits and challenges. A Report of the CSIS Energy & National security program; 2010.
- [49] Wang Q, Chen X, Jha AN, Rogers H. Natural gas from shale formation—The evolution, evidences and challenges of shale gas revolution in United States. *Renew. Sustain. Energy Rev*. 2014;30:1–28.